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Performance Analysis of Hybrid Ultra Capacitor (HUC) based Solar Microgrid for Household Applications

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Abstract

Localised power generation and consumption using a solar-based hybrid micro-grid system are gaining predominance in remote locations where conventional transmission of power from far off substations work out to be uneconomical. Since the peak irradiance from the sun lasts for 4-6 hours per day, a hybrid micro-grid with batteries for storing energy is usually adopted. This study considered a typical household load of 3kW comprising resistive and inductive loads. Sudden surges will be caused by switching ON/OFF of any load, and in particular, switching ON of inductive loads (such as fans, washing machines and mixer) will further contribute to transients. These sudden changes in loads harm the cyclic life of the battery. A viable solution to overcome the above problem is to use Hybrid Ultra Capacitors (HUC) as an assistant to the Batteries. These HUC banks can take over the surge loads, whereas Batteries can focus on delivering steady power. Such a combination has the potential to enhance the battery's life. This study discusses the performance of Hybrid Ultra Capacitor (HUC) based Hybrid Energy Storage System (HESS) in a 3kW Solar MicrogriAU: Please prod system by evaluating the electrical parameters involving experiments with different loads.

Keywords: Electric Vehicles, Hybrid Ultra Capacitors, Power Batteries, Solar Micro-grid

1. Introduction

Batteries are energy density devices, and Ultra Capacitors are power density devices. Traditional Ultra Capacitors were of Electrochemical Double Layer Capacitors (EDLC) type. In this work, Hybrid Ultra Capacitors of rating 12V , 1250F, Electrodes - (+) & Activated Carbon (-), Gel Electrolyte (aq.) were used[1]. In this study, we have incorporated an Energy Management System to balance the power demands within HESS by enabling the Battery bank to focus on delivering steady power and allowing the HUC bank to handle surge power demands. Such a HESS has the potential to enhance the battery's life[2–4]. This study analyses the performance of HESS in handling surge power demands.

2. Literature Review

Electrostatic and Electrolytic capacitors are traditionally limited to a capacitance of up to a few millifarads. Whereas, Electrochemical capacitors have a higher capacitance of order of a few hundred Farad to few Kilo Farad[5–7] as they use an electrolyte instead of a separate dielectric and store the charges on the interfacial surface between the electrode and the electrolyte. Because of the high capacitance, these electrochemical capacitors display high energy density capabilities. Electrochemical capacitors are classified into different generations depending on the electrode and electrolyte used[1]. Among electrochemical capacitors, Hybrid Ultra Capacitors leverage the advantages of both EDLC and Pseudocapacitors by having one electrode

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as a battery-like electrode and the other electrode as an EDLC type[8]. Our study used Hybrid Ultra Capacitors with asymmetric electrodes and aqueous electrolytes to tap the advantages of better cyclic stability, high power performance, and higher specific capacitance.

3. Methodology

3.1 Experimental Setup

In this experiment, 3kW solar microgrid comprising PV Array, Inverter and accessories, 48V/600Ah Lead-Acid Battery Bank, 48V/625F HUC Bank, Energy Management System (EMS), AC loads and Datalogger were used. The HUC Bank comprises four units connected in series with two such strings connected in parallel. A constant 3kW lighting load (baseload) and 1hp motor (surge load) were used as the experimental load for the study. A timer circuit was used to switch on the motor for approximately two seconds. Figure 1 depicts the System architecture. Terminal electrical parameters at each system component were monitored using a data logger.

3.1.1 Experiments Studied

Following four experimental scenarios were studied for the same load profile with ON/OFF conditions of PV output and HUC Banks as depicted in Table 1.

This paper presents the analysis of Voltage (V), Current (I), Power (P), Energy (E) parameters monitored at the output terminals of system components for the experimental scenarios mentioned in Table 1.

3.2 Load Profile

The load profile used for the study is depicted in Figure 2. The 3kW base lighting load were switched ON for 5 seconds, during which a 1hp motor was switched ON for 2 seconds using a timer circuit. The load profile in Figure 2 is chosen to analyse the performance of HESS in handling surge power demands which a household load might experience during switching ON/OFF of lighting and fan loads. Such short duration load is called a pulse power profile and is used to quickly discern the performance of HUC in responding to the surges[9]. Analysis of the system performance was studied under three sections.

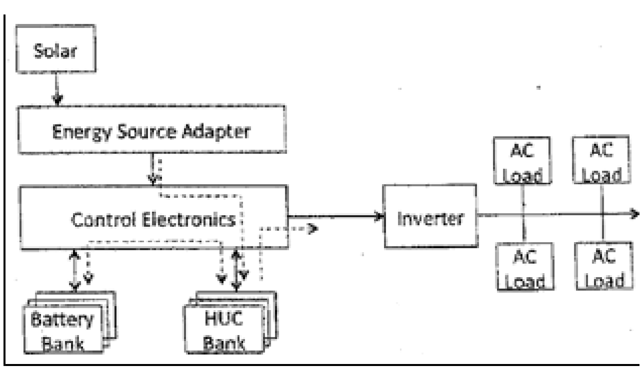

Figure 1. System architecture.

Table 1. Experimental scenarios studied

Experiment	PV	Battery	HUC	Load
A	OFF	ON	OFF	ON
B	OFF	ON	ON	ON
C	ON	ON	ON	ON
D	ON	ON	OFF	ON

1. Section A - Entire load profile of 5s duration
2. Section B – Transient Portion (2s duration) of load profile during which baseload and surge load was ON
3. Section C - Sub-transient state condition (82ms duration) in which the load current oscillated before stabilising

The load profile has been generated with the same sequence of switching operation of lighting loads for all 4 Experiments studied.

4. Experimental Results and Analysis

4.1 Analysis of Entire Load Profile (Section A)

Waveforms captured during the experiment are depicted in Figures 3, 4, 5 and 6.

The following observations were made from Table 2

4.1.1 Load Parameters

The PU values of the load voltage RMS are same for all the Experiments suggesting that, usage of HUC in HESS has not led to any load voltage fluctuations.

4.1.2 Battery Parameters

Upon comparison of initial battery voltage for Experiment C & D with that of Experiment A & B, it is found that the

Table 2. Analysis of entire load profile (Section A)

Parameters and Base Value	Experiment	Per Unit (PU). Values			
		PV	Bt.	HUC	Load
Analysis of Entire load profile					
Voltage Solar = 58.45V Avg. Battery = 48.56V Avg. HUC = 45.79V Avg. Load = 229.40V RMS	A	-	1.00	-	1.00
	B	-	1.00	1.00	1.00
	C	1.00	1.04	1.05	1.00
	D	1.06	1.06	-	1.00
Current Solar = 34.48A Avg. Battery = 74.15A Avg. HUC = 7.70A Avg. Load = 14.62A RMS	A	-	1.00	-	1.00
	B	-	0.90	1.00	0.85
	C	1.00	0.31	0.67	1.04
	D	0.67	0.48	-	1.02
Average Power Solar = 2015W Source Battery = 3315W Source HUC = 236W Source Load = -2773W Sink	A	-	1.00	-	1.00
	B	-	0.96	1.00	0.94
	C	1.00	0.34	0.72	1.14
	D	0.72	0.54	-	1.12
Energy Solar = 10074Ws Source Battery = 16445Ws Source HUC = 1532Ws Source Load = -13844Ws Sink	A	-	1.00	-	1.00
	B	-	0.97	1.00	0.94
	C	1.00	0.38	0.72	1.15
	D	0.72	0.54	-	1.13

former is marginally higher than the later suggesting that in presence of Solar, the battery has a higher Initial State of Charge (SOC).

The current values, average power and energy for Experiment C & D are relatively much lesser than Experiment A & B, indicating that the battery has acted as a secondary source, allowing PV to take a lead role.

4.1.3 HUC Parameters

The Initial HUC voltage is higher for Experiment C than Experiment B, suggesting a higher Initial State of Charge (SOC) for HUC due to solar.

The current values, average power and energy for Experiment C are marginally lower than that of Experiment B, suggesting that in the presence of solar, the power and energy demand from HUC during the surges was lower as solar has acted as the primary source.

4.1.4 Solar Parameters

The current values, average power and energy for Experiment D are marginally lower than Experiment C suggesting that in the absence of HUC, the solar need not accommodate the extra burden of charging the HUC.

4.2 Analysis of Transient Part of the Load Profile (Section B)

The following observations were made from Table 3

4.2.1 Load parameters

The average power and energy for Experiment C & D are higher than Experiment A & B, suggesting that the presence of solar has aided in the quick deliverance of power during surges.

4.2.2 Battery Parameters

The average power and energy delivered by the battery in Experiment B are less than that of Experiment A, suggesting the effectiveness of HUC in handling the surge loads during the transient period.

The average power and energy of the battery in Experiment C are less than that of Experiment D, again

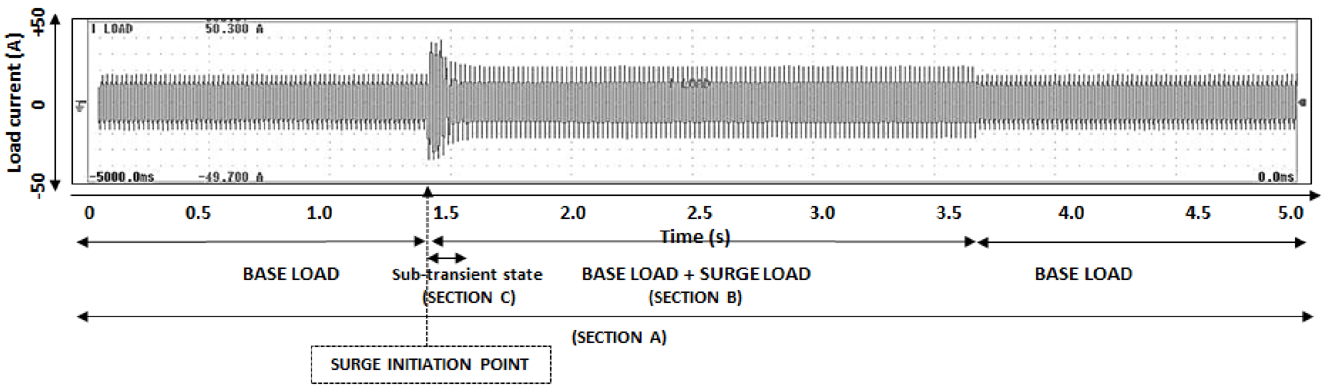

Figure 2. Load profile.

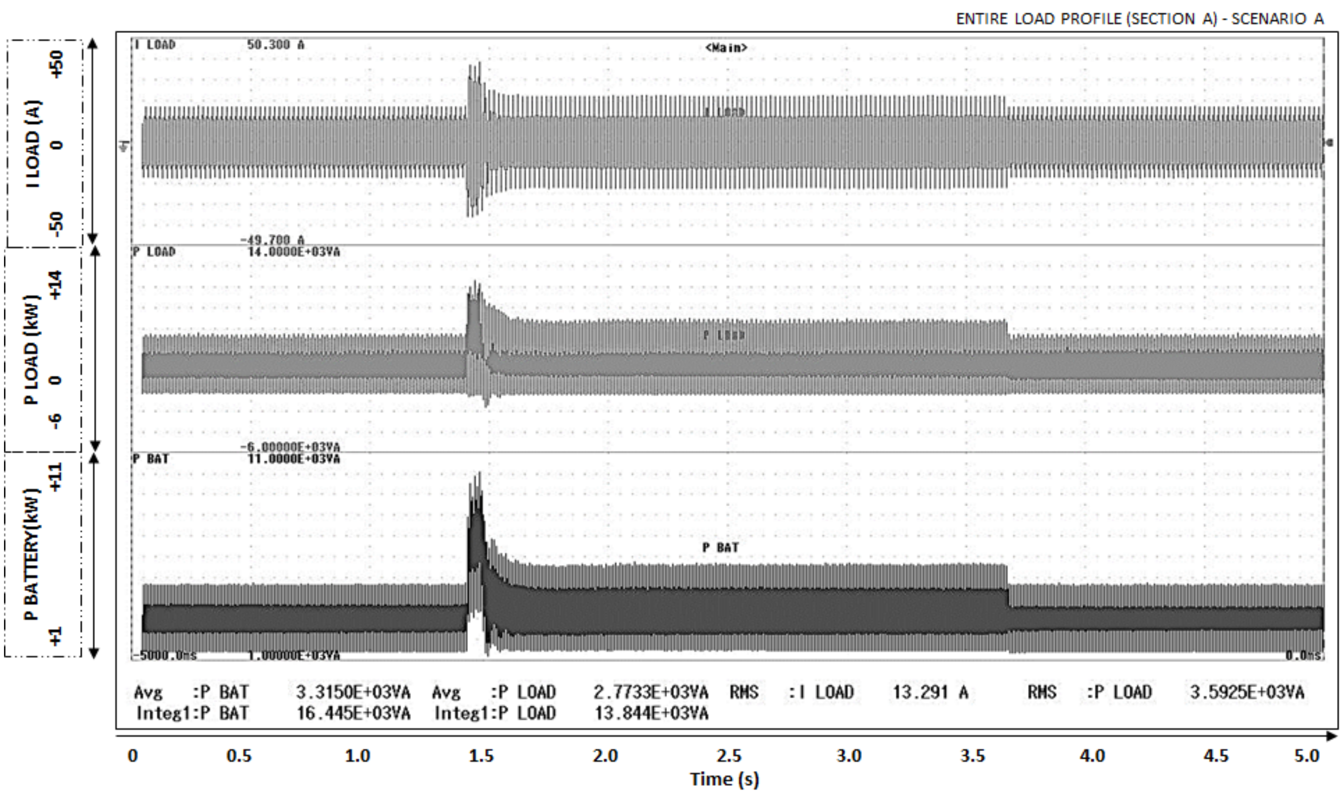

Figure 3. Analysis of entire load profile (Sec A) - Experiment A.

suggesting the effectiveness of HUC even in the presence of solar power.

4.2.3 HUC Parameters

The average power and energy for Experiment C are lesser than Experiment B suggesting that the presence of solar has reduced the power and energy demand from HUC during the surges.

4.3 Analysis of Sub-transient Part of Load Profile (Section C)

The following observations were made from Table 4

4.3.1 Load Parameters

Despite the same load switching sequence, the current values, average power for Experiment C & D are higher

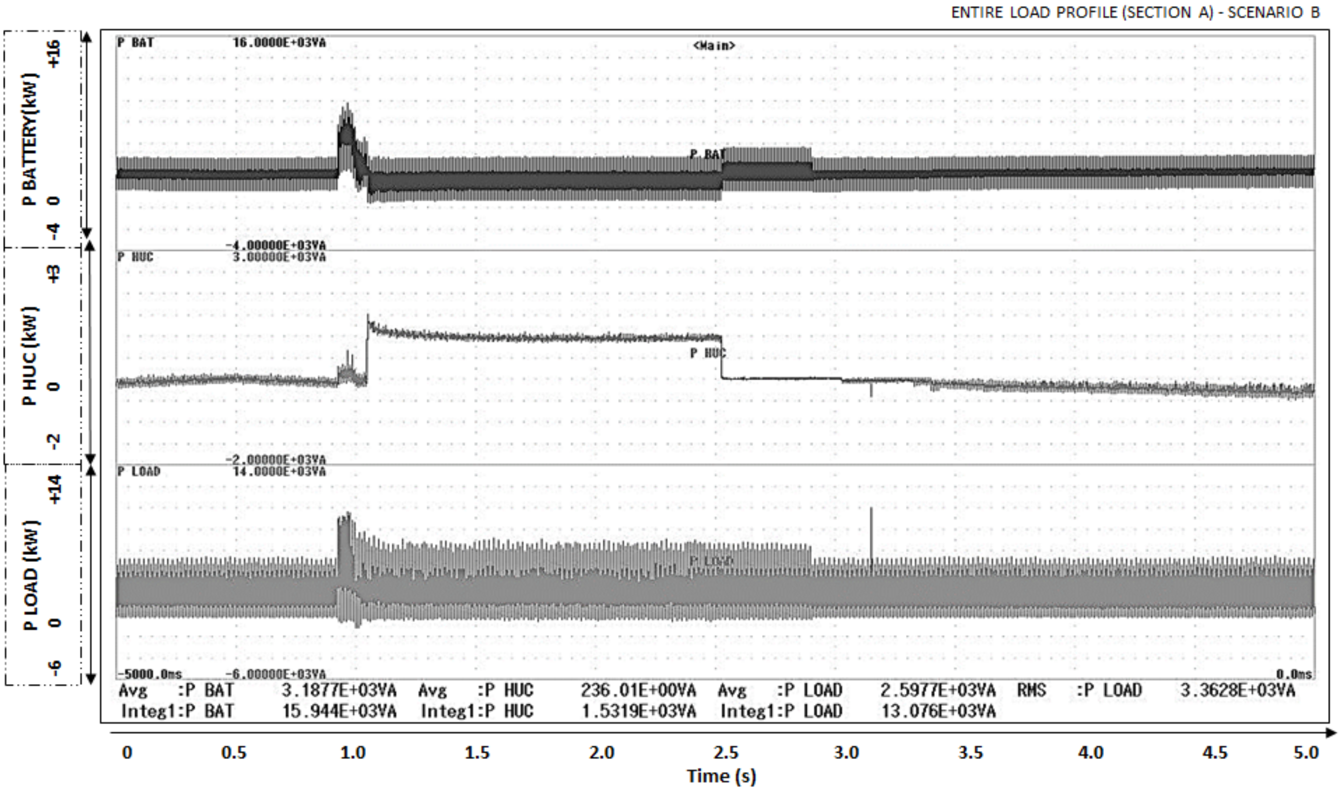

Figure 4. Analysis of entire load profile (Sec A) - Experiment B.

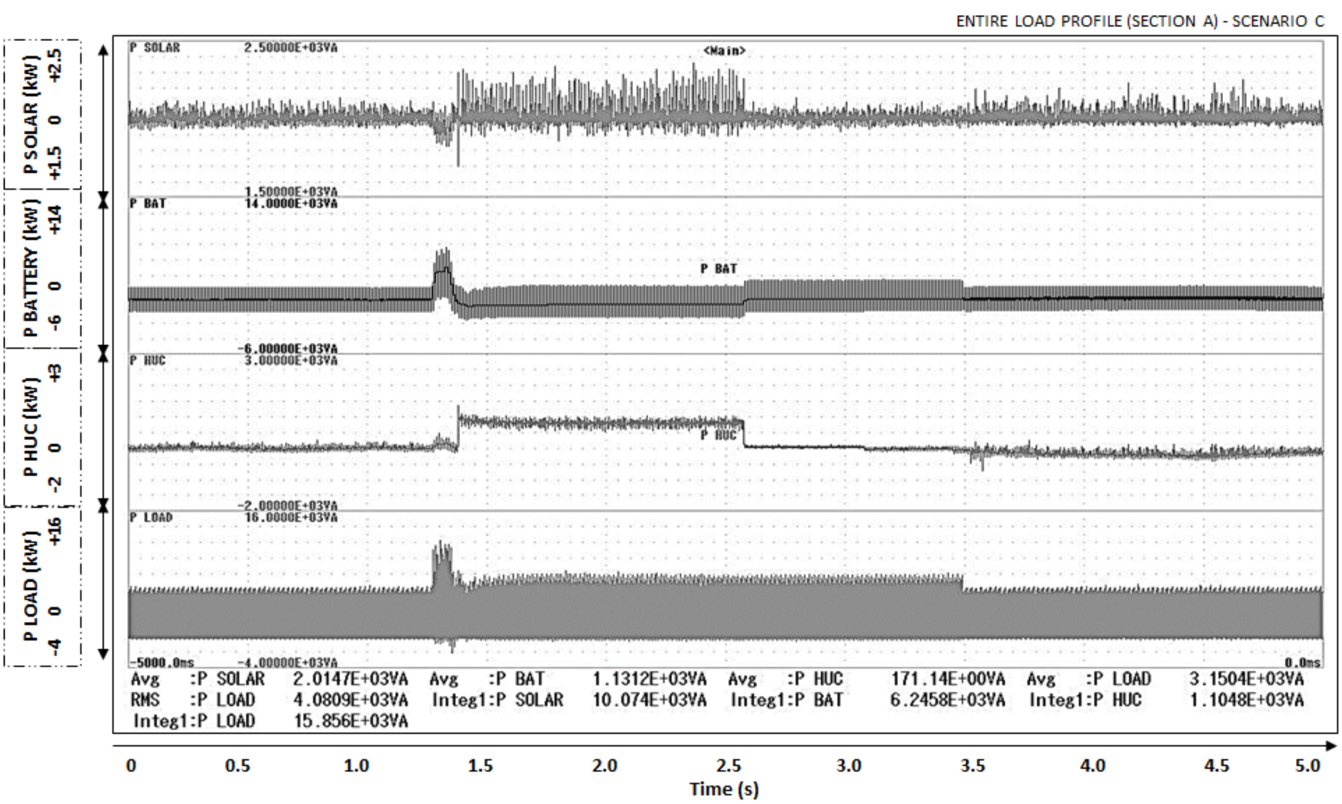

Figure 5. Analysis of entire load profile (Sec A) - Experiment C.

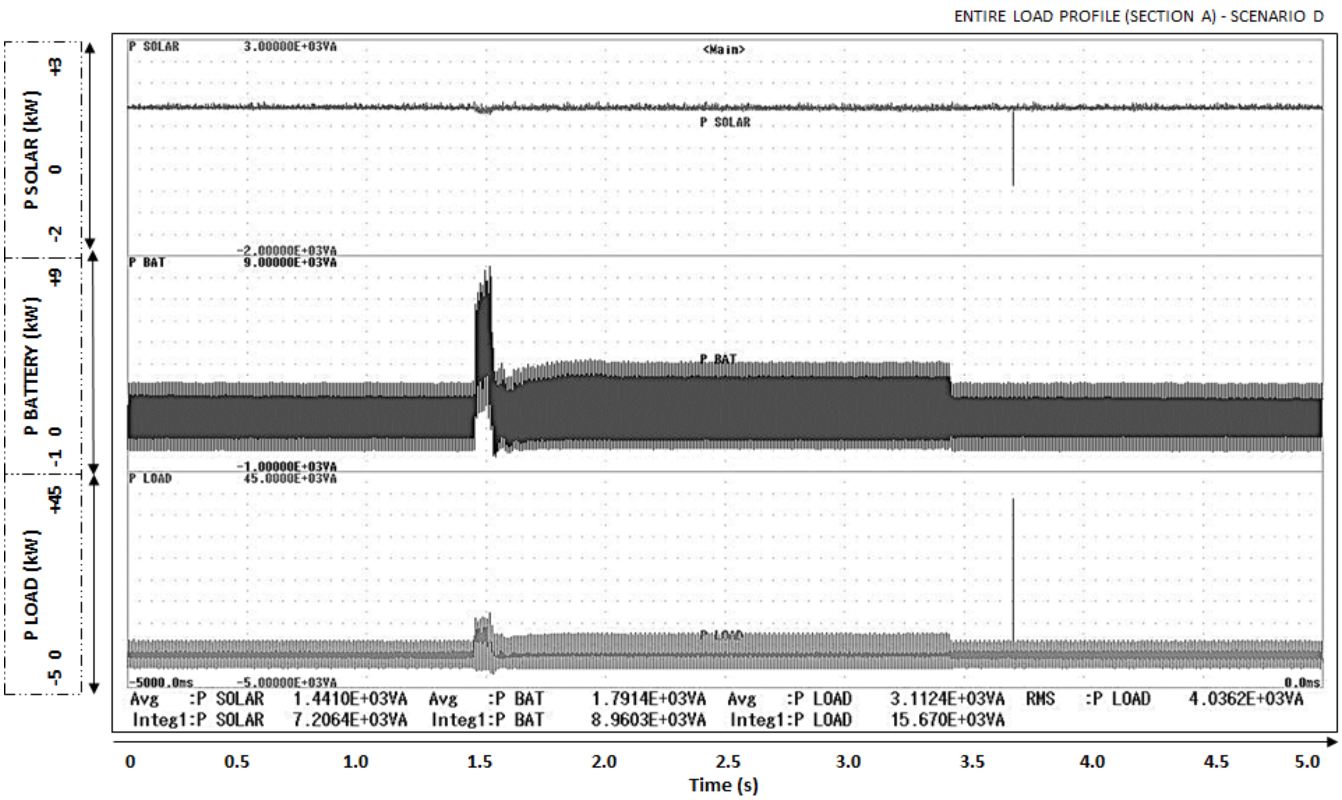

Figure 6. Analysis of entire load profile (Sec A) - Experiment D.

Table 3. Analysis of transient part of the load profile (Section B)

Parameters and Base Value	Experiment	Per Unit (PU). Values			
		PV	Bt.	HUC	Load
Analysis of Transient part of the load profile					
Average Power Solar = 2015W Source Battery = 3608W Source HUC = 757W Source Load = -3007W Sink	A	-	1.00	-	1.00
	B	-	0.84	1.00	0.95
	C	1.00	0.31	0.62	1.13
	D	0.71	0.59	-	1.13
Energy Solar = 4481Ws Source Battery = 8190Ws Source HUC = 1504Ws Source Load = -6890Ws Sink	A	-	1.00	-	1.00
	B	-	0.73	1.00	0.83
	C	1.00	0.36	0.70	1.11
	D	0.64	0.52	-	1.00

than that of Experiment A & B. It points out that the presence of solar has aided in handling surge loads.

4.3.2 Battery Parameters

Upon comparison of Experiment A & B, it is seen that the surge current and average power delivered during the sub-transient period by the battery is not lower in the presence of HUC, questioning the effectiveness of HUC in handling the sub-transient surge loads.

4.3.3 HUC Parameters

The base values of HUC and Battery show that the current surge, average power delivered by the HUC during the sub-transient period is very low compared to that of the

Table 4. Analysis of Sub-transient part of the load profile (Section C)

Parameters and Base Value	Experiment	Per Unit (PU). Values			
		Solar	Battery	HUC	Load
Analysis of Sub-transient part of the load profile					
Current Surge Solar = 34.49A Avg. Battery = 225A Max. HUC = 42A Max. Load = 74.80A Peak-Peak	A	-	1.00	-	1.00
	B	-	1.00	1.00	0.96
	C	1.00	0.70	0.58	1.13
	D	0.68	0.82	-	1.11
Voltage drop Solar = 8.60V Battery = 6.80V HUC = 26.00V Load = Nil	A	-	1.00	-	-
	B	-	0.85	1.00	-
	C	1.00	0.94	0.82	-
	D	1.12	1.12	-	-
Average power Solar = 1956W Source Battery = 4339W Source HUC = 123W Source Load = -3565W Sink	A	-	1.00	-	1.00
	B	-	1.41	1.00	1.32
	C	1.00	0.93	1.13	1.59
	D	0.71	1.04	-	1.53
Average energy Solar = 158Ws Source Battery = 860Ws Source HUC = 10Ws Sink Load = -712Ws Sink	A	-	1.00	-	1.00
	B	-	0.56	1.00	0.53
	C	1.00	0.38	1.20	0.66
	D	0.73	0.44	-	-0.65

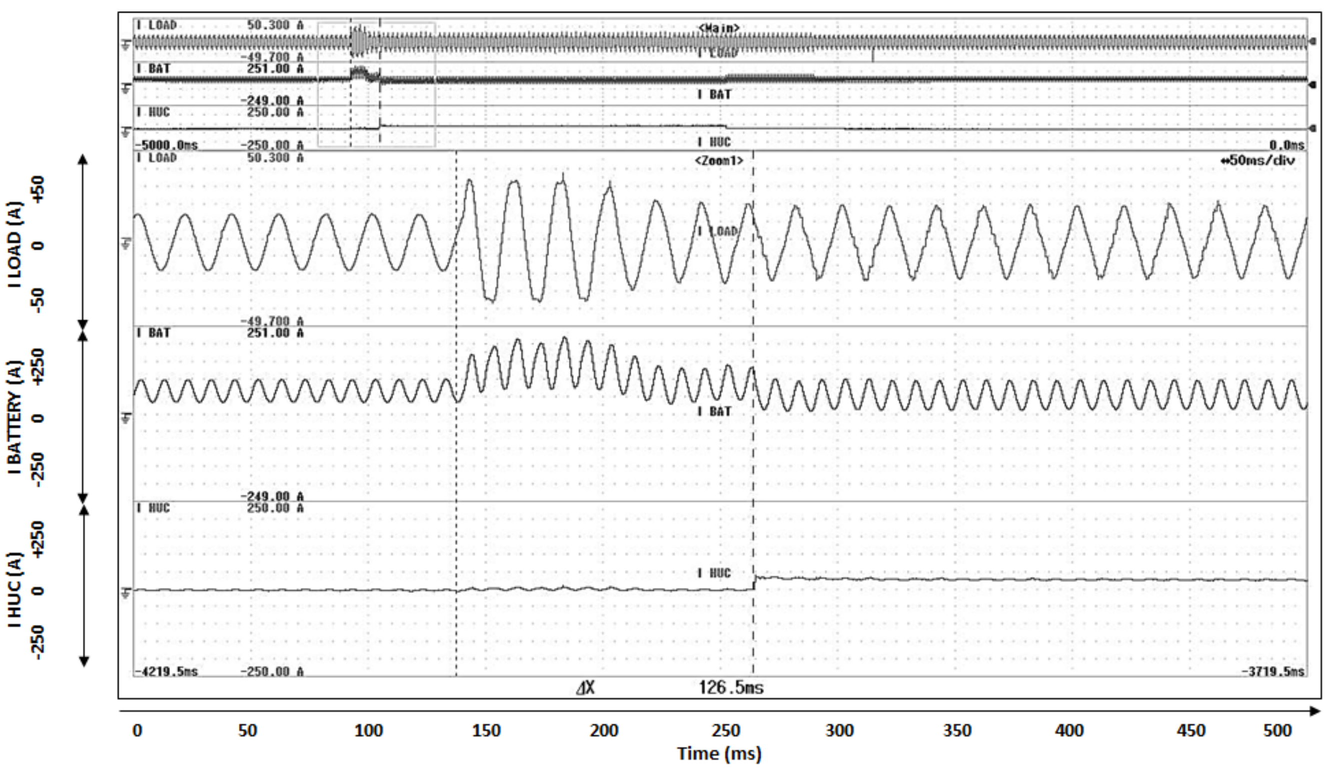

Figure 7. Delay analysis from the current profiles

battery. The low power deliverance by HUC during sub-transient period could be attributed to two factors.

1. The sizing of the HUC bank is lower compared to the battery capacity.
2. HUC has been ineffective in handling the sub-transient surge loads.

It was observed that,

The above comparison of ratios suggests that though the HUC bank's sizing is lower than the battery capacity, there is more reason why HUC has been so ineffective in handling sub-transient surge loads.

Upon further analysis it was observed that HUC delivered for 1.48sec out of 2sec transient period and HUC delivered after 126.5ms from the start of the sub-transient part (refer Figure 7) whereas battery delivered after 2ms from the start of transient. It is to be noted here that the sub-transient phase lasted for only 82ms and HUC has started delivering only after 126.5ms after the surge initiation point, this supports our observation that in the present study, HUC has not been effective in handling sub-transient surge loads. The cause is attributed to the delay of 126.5ms taken by HUC in responding to the surge power requirement.

Two factors could be attributed to this delayed response:

- Charge mobility issues owing to tiny pore size on the surface of HUC's amorphous carbon electrode
- Propagation delay in the EMS circuit

Figure 7 reveals that the rate of rising of HUC current is very steep, and the rise time of HUC current is less than 1ms, which indicates that the delayed response could be better attributed to the propagation delay of the EMS circuit rather than charge mobility issues of the HUC's electrode.

5. Conclusion

This study observed that integration of HUC with battery in a HESS has not to lead to any noticeable load voltage fluctuations. Compared to a non-solar system, a solar-based system was more capable of handling surge loads. HUC was found to be effective in handling transient surge loads, but it was found to be not so effective in handling sub-transient surge loads. Upon detailed analysis, it was noticed that HUC has failed to even start its discharge during the sub-transient period due to the EMS circuit's propagation delay. In contrast, once the EMS has triggered the HUC, it has discharged instantly (less than 1ms) without any significant delay attributed to the charge mobility issues out of the HUC's electrode.

6. Acknowledgement

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